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EFFECTS OF ADVANCED FUEL INJECTION STRATEGIES ON DI DIESEL EMISSIONS

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SUMMARY/OVERVIEW:

The focus of the program is developing engineering models for Diesel emissions and performance that (1) stand alone as preliminary design tools, (2) provide submodels for CFD, spray-marching, and cycle simulations, and (3) offer real-time algorithms for control of smart engines. These models, because of their simplicity, also provide the design engineer with valuable insight into the predominate processes governing engine emissions and performance. The model equations are derived from first principles and are based on Damköhler numbers describing the pollutant chemistry and fluid flow processes. To date emissions of oxides of nitrogen (NO_x) have received primary emphasis. Both quasi-steady and dynamic models have been developed and examined with data from various engines. Development of similar models for particulate emissions and power density continues. One of the topics examined in the past year is the effect of multiple fuel injections on emissions of nitric oxide.

TECHNICAL DISCUSSION:

Due to recent advances in injector technology, many modern injectors now have the ability to inject multiple pulses of fuel into the cylinder during a given cycle. Experimental engine results using injectors capable of multiple injections are plentiful in the literature and indicate that NO_x, particulates, and/or fuel consumption may be reduced by using optimized fuel injection schemes. However, methods of determining optimized fuel injection strategies have not been presented. To date, modeling of multiple injections has been accomplished through the use of computational fluid dynamics codes and cycle simulation type codes. These codes, while providing an estimation of the expected engine performance and emissions for a given injection scheme, provide little insight as to what the best injection scheme is. Typically various injection schemes are modeled in hopes of finding one which approaches the optimum.

The objectives of the present work are to develop semi-empirical models for engines using multiple injections that can be used to estimate engine performance and emissions a priori and also provide the design engineer with insight into the optimization process. Efforts to date have been focused on the development of a quasi-steady NO_x model. This model is a modification to that originally developed at Vanderbilt under a previous ARO grant for use with single injections [1], which was successful in correlating NO_x emissions from a 2.2L high speed direct injection (HSDI) Diesel engine [2].

Model Formulation for Single Injections: The model is based on the assumption that NO forms in the stoichiometric contour surrounding the fuel plume (see Fig. 1; referred to as zone 1 below). The characteristic temperature and pressure for this zone are the start of combustion, stoichiometric flame temperature ($T_{\phi=1}$) and pressure. The NO chemistry is based on a skeletal mechanism for NO_x emissions [1] which includes reactions from the extended Zeldovich

mechanism [3] and select reactions from the nitrous oxide mechanism [4]. Assuming O-atom in equilibrium, N-atom in steady-state, and NO decomposition negligible, the chemical kinetic time for NO formation can be defined as

$$\tau_{no} = \frac{[NO]_{eq1'}}{2[O]_{eq1}[N_2]_{eq1}(k_{1f} + k_{5f})} \tag{1}$$

where k_{1f} and k_{5f} are the rate coefficients for the leading reaction in the extended Zeldovich mechanism and the termolecular reaction of the nitrous oxide mechanism, respectively. $[NO]_{eq1'}$ is a normalizing concentration that will be shown to cancel in the final form of the model equation.

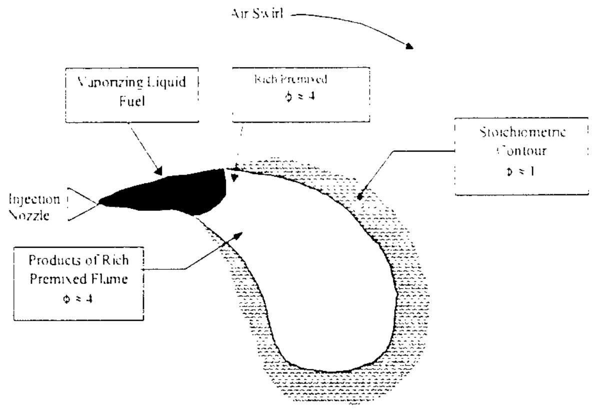

Figure 1: Quasi-steady schematic of DI Diesel fuel plume based on laser diagnostic results of Flynn et al. [5]. NO chemistry occurs in the stoichiometric contour of the spray plume.

The residence time for a NO forming eddy in the NO formation zone (mixing time for NO formation) was found in previous work to be given by [2],

$$\tau_{fi,no} = \left(\frac{We}{Re}\right)^{1.5} \frac{l_{bowl}}{V_{fuel}} \tag{2}$$

where l_{bowl} is the radius of the bowl and the subsript *fi* stands for fuel injection because the fuel injection event dominates the mixing process. Here the Weber and Reynolds numbers have been defined as

$$We = \frac{\rho_{fuel} d_{noz} V_{fuel}^2}{\sigma_{fuel}} \qquad Re = \frac{\bar{S}_p B}{\nu_{air}} = \frac{2LNB}{\nu_{air}} \tag{3}$$

where V_{fuel} is the peak injection velocity. The mass of NO_x emitted from the combustion chamber per firing stroke is now given by

$$m_{NO_2}(gNO_2/st) = m' V_1 \frac{\tau_{fi,no}}{\tau_{no}} [NO]_{eq1'} \tag{4}$$

where V_1 is the volume of the NO formation zone (calculated using the ideal gas law) and m' is a model constant that accounts for the characteristic mixing time being proportional to the actual mixing time instead of equal.

Model Formulation for Multiple Injections: For the work presented here, the reduction in NO_x due to the use of multiple injections is of concern. Therefore, the mass of NO_x emitted by the engine when using multiple injections is normalized by the NO_x emissions from the engine at the same speed and load condition when using single injection, thereby allowing the model constant, as well as many other terms, to be cancelled. The above model is modified for use with multiple injections by considering each injection separately. The model equation can now be stated as,

$$m^* = \frac{m_{no,multiple}}{m_{no,single}} = \sum_{i=1}^{\#inj}\left(y_i \times \frac{T_{\varphi=1,i}}{T_{\varphi=1,single}} \times \frac{P_{soc,single}}{P_{soc,i}} \times \frac{\tau_{no,single}}{\tau_{no,i}} \times \frac{V_{inj,i}^2}{V_{inj,single}^2} \right) \tag{5}$$

where y_i is the mass fraction of fuel in injection pulse i, and the injection velocities are evaluated at their peaks for each injection pulse. Note that in Eq. (5) the definition of the mixing time for NO formation given in Eq. (2) has been used as well as substituting the ideal gas law for the volume of the NO formation zone, with many of the terms canceling due to the normalization. In the above derivation of the model, the characteristic temperature of the NO formation zone was calculated at the SOC conditions, which were taken to be the bulk temperature and pressure in the cylinder. For application to the multiple injection case the conditions at the start of combustion for each injection pulse are taken to be the motored pressure and temperature in the cylinder.

Evaluation of Experimental Data: Engine tests were conducted on a 1.2L HSDI Diesel engine (0.3 L/Cyl.) equipped with a common rail fuel injection system capable of multiple injections [6]. For the present analysis the effect of multiple injections on emissions and performance was evaluated by holding the engine speed, brake mean effective pressure (BMEP), and exhaust gas recirculation (EGR) rate constant while changing the injection strategy between single, double and triple injections. Presently three such conditions are available for analysis. The injection rate and normalized cumulative heat release profiles for one condition are presented in Fig. 2.

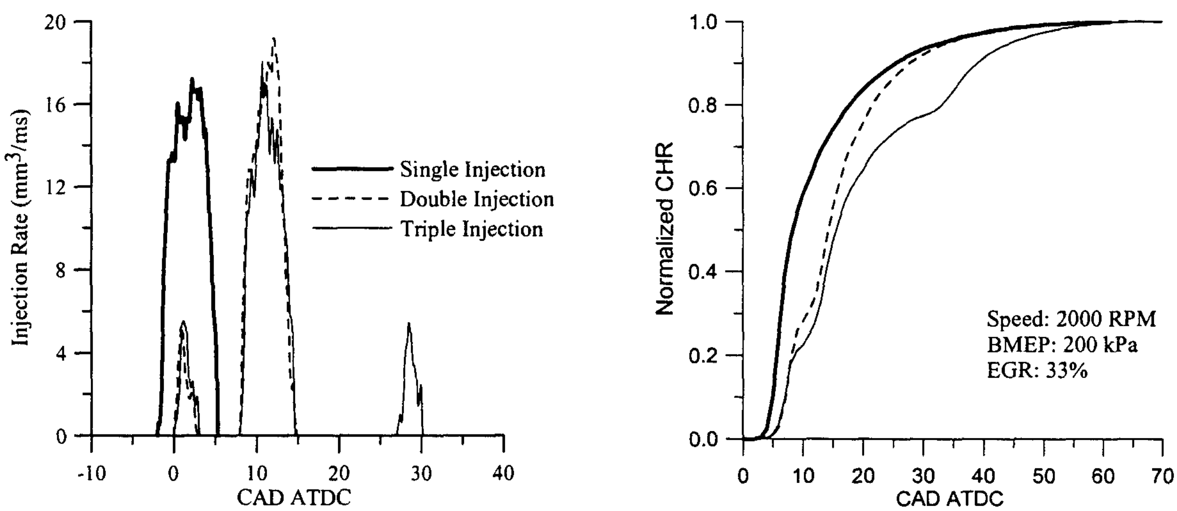

Figure 2: Injection rate and normalized cumulative heat release (CHR) profiles for the 2000 RPM, 200 kPa BMEP, 33% EGR operating condition. For the engine tests the engine speed, BMEP, and EGR rate were held constant while the injection profiles were varied from single to double to triple injections.

The predicted normalized emissions of NO_x from the engine using Eq. (5) are compared with the measured normalized emissions of NO_x from the engine in Fig. 3. If the model were

perfect the data would lie on the 45° line that has been included on the graph. The results are very promising, as all the data are near the line.

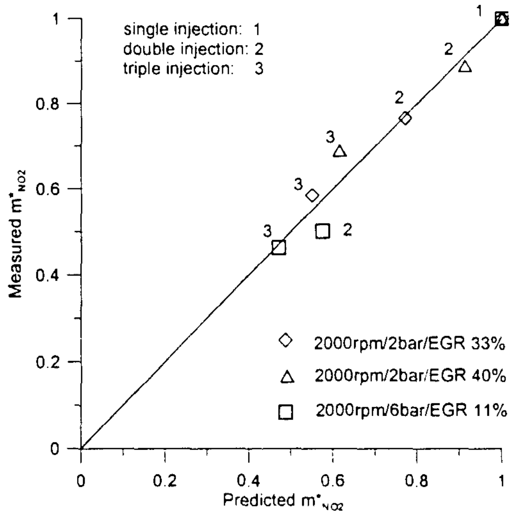

Figure 3: Normalized measured NO_x emissions versus predicted normalized NO_x emissions using Eq. (5).

Future efforts are focused on the continued development and validation of the model presented here and a cycle simulation type model targeted for use in DI Diesel engine optimization. The cycle simulation code will incorporate a dynamic NO_x model previously developed at Vanderbilt, as well as soot, combustion, and heat loss models. Also, tests have begun on a light-duty DI Diesel engine, which examine the effects of injector type, injection strategy (including multiple injections), bowl geometry, boosting, aftercooling, and EGR on engine operation and emissions. The results from these engine tests will be used for further model development and validation.

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